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The Inductive Coupling of the Magnets in MICE and its Effect on Quench Protection*

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DISCLAIMER

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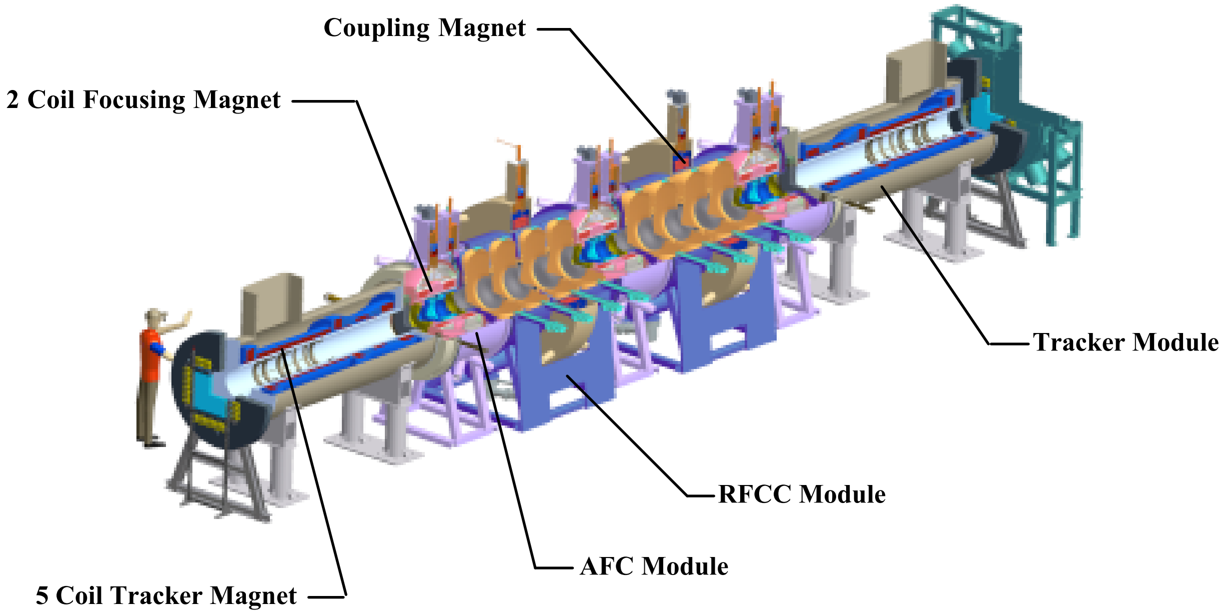

Fig. 1. The MICE Cooling channel with the two tracker magnets. The 18-coil system is coupled together magnetically.

***Abstract*—The inductive coupling between various MICE magnet circuits is described. The consequences of this coupling on magnet charging and quenching are discussed. Magnet quench protection is achieved through the use of quench-back. Calculations of the quenching of a magnet due to quench-back resulting from circulating currents induced in the magnet mandrel due to quenching of an adjacent magnet are discussed. This report describes how the MICE magnet channel will react when magnets in that channel are quenched.**

***Index Terms*—S/C Solenoids, and Inductive Coupling**

I. INTRODUCTION TO MICE

The development of a muon collider or a neutrino factory requires that beams of low emittance muons be produced. A key to the production of low emittance muons is muon cooling. A demonstration of muon cooling is essential to the development of muon accelerators and storage rings [1], [2]. The international Muon Ionization Cooling Experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting magnets [3] that may be useful for a neutrino factory.

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The full MICE channel is shown in Fig. 1. The experiment consists of two tracker modules at the ends of a muon-cooling channel. The cooling channel consists of three absorber focus coil modules (AFC modules) and two RF coupling coil modules (RFCC modules).

II. THE MICE MAGNETS

The tracker module consists of a five-coil superconducting magnet [4]. The three spectrometer coils (End 1, Center, and End 2) are used to generate a uniform 4 T field in a 1-m long region that is 300-mm in diameter. The uniform field region contains five planes of scintillating fibers used to measure the muon emittance. There are two match coils match 1 and match 2 in the tracker solenoid that are used to match the beam into the uniform field region. Table 1 presents the tracker magnet coil parameters.

Ionization cooling of muons means that muons have their momentum reduced in both the longitudinal direction and the transverse direction by passing them through a low Z absorber. (Liquid hydrogen is best.) The absorber is located within the warm bore of a two-coil superconducting solenoid that is part of the AFC module [5]. The purpose of the magnet is to focus the muon beam so that it has low β. The focusing magnet parameters are shown in Table 2.

RF cavities are used to re-accelerate the muons to their original longitudinal momentum. These cavities are surrounded by the superconducting coupling solenoid [6]. The coupling coil parameters are shown in Table 3.

TABLE 1. THE NOMINAL DESIGN PARMAMETERS FOR THE MICE DETECTOR SOLENOID COILS

Parameter	Match 1	Match 2	End 1	Center	End 2
Coil length (mm)	198	197	110	1294	110
Coil inner radius (mm)	258	258	258	258	258
Coil thickness (mm)	46.2	26.4	61.6	24.2	68.2
Number of layers	42	24	56	22	62
Number of turns per layer	120	119	66	784	66
Coil overall current density (A mm^{-2})	147.6	161.3	136.8	146.9	145.4
Coil current (A)	267.8	293.8	249.5	265.9	265.2
Coil self inductance (H)	12.8	4.3	9.6*	41.6*	11.4*
Coil Stored Energy at Current above (MJ)	0.47	0.20	0.30	1.49	0.40

* Note the self-inductance of the 3 spectrometer-coils connected in series is 78 H. At 266 A, the stored energy is 2.8 MJ.

TABLE 2.
THE BASIC PARAMETERS OF THE FOCUSING MAGNET

Parameter	Non-flip	Flip
Coil separation (mm)	200	
Coil length (mm)	210	
Coil inner Radius (mm)	263	
Coil thickness (mm)	84	
Number of layers	76	
Number of turns per layer	127	
Magnet J (A mm^{-2})*	71.96	138.2
Magnet Current (A)*	130.5	250.7
Magnet Self Inductance (H)	137.4	98.6
Magnet Stored Energy (MJ)*	1.17	3.10

* Worst case values based on p = 240 MeV/c and β = 420 mm

TABLE 3.
DESIGN PARAMETERS FOR THE COUPLING MAGNET

Parameter	
Coil Length (mm)	250
Coil Inner Radius (mm)	725
Coil Thickness (mm)	116
Number of Layers	104
No. Turns per Layer	151
Magnet J (A mm^{-2})*	115.5
Magnet Current (A)*	213.2
Magnet Self Inductance (H)	563
Magnet Stored Energy (MJ)*	13.6

* Worst case design based on p = 240 MeV/c and β = 420 mm

Table 2 shows two operating modes for the focusing magnet, the flip mode where the field polarity changes as one goes through the magnet center along the magnet axis and the non-flip mode where the field polarity doesn't change. When MICE is run in the flip mode, the field polarity changes three times along the channel. In the non-flip mode there is no polarity change. MICE will be operated in both modes. The cases shown in Table 2 represent the worst cases for MICE.

The entire MICE channel (including the tracker module) consists of eighteen superconducting coils that are located within the seven cryostats. All eighteen coils are coupled with each other. The greatest coupling will be with adjacent coils. A quench of one magnet can affect other magnets.

III. MICE MAGNET QUENCHES

The primary mode of quench protection for the MICE focusing magnet is through quench-back from the 6061-T6-aluminum mandrel that is around the two coils. Each focusing magnet consists of two coils hooked in series either in the flip mode or the non-flip mode depending on the experiment operating-configuration. Fig. 2 shows the current decay and the coil hot spot temperature as a function of the time from the start of a magnet quench. Fig. 2 applies for the focusing magnet hooked up in the worst-case flip mode (see Table 2). The two cases shown are for a quench of a single focusing magnet and a quench of the three magnets hooked in series. From Fig. 2, one can see that the three magnets quench is similar a single magnet. The quench-back time is short (~1.1 s) so the energy is more evenly spread between magnets. Thus connecting the three focusing magnets together in series appears to be attractive [7], [8]. At the end of the quench the mandrel temperature is a lot cooler than the average coil temperature (52 K versus 82 K).

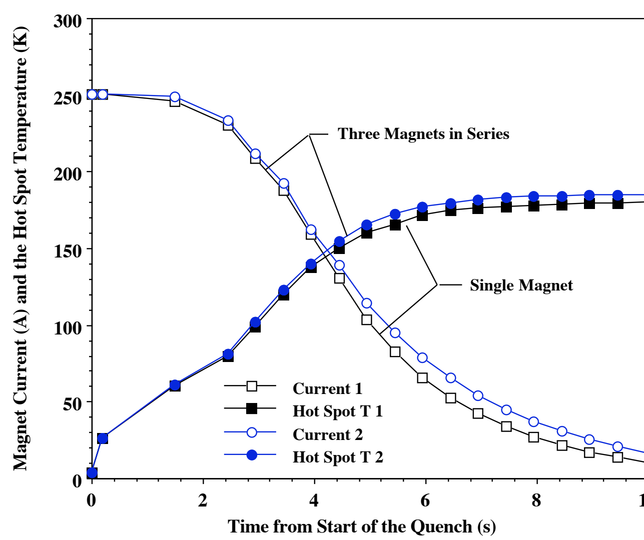

Fig 2. A quench of the one and three focusing magnets.

TABLE 4. THE INDUCTANCE MAP FOR THE MICE MAGNET CIRCUITS IN THE FLIP MODE

	S	M2	M1	F	C1	C2
S	155.8	1.283	0.711	0.190	0.549	0.549
M2	1.283	6.880	0.809	0.121	0.132	0.132
M1	0.711	0.809	26.24	1.160	0.441	0.441
F	0.190	0.121	1.160	304.4	5.569	5.569
C1	0.549	0.132	0.441	5.569	563.0	6.713
C2	0.549	0.132	0.441	5.569	6.713	563.0

TABLE 5. THE INDUCTANCE MAP FOR THE MICE MAGNET CIRCUITS IN THE NON-FLIP MODE

	S	M2	M1	F	C1	C2
S	156.5	1.285	0.721	0.705	0.810	0.810
M2	1.285	6.886	0.809	0.278	0.161	0.161
M1	0.721	0.809	26.46	1.963	0.631	0.631
F	0.705	0.278	1.963	416.3	17.91	17.91
C1	0.810	0.161	0.631	17.91	563.0	6.713
C2	0.810	0.161	0.631	17.91	6.713	563.0

Similar quench studies were done on the coupling magnet (see Table 3) [7], [9]. Figure 3 shows the current decay of the coupling magnet and the coil hot-spot temperature as a function of the time from the quench start. The quench was simulated for a single coupling magnet and for both magnets in series. The results of the quench study suggest that the two magnets could be connected in series, but the hot-spot temperature is high. The quench back time is longer (~2.2 s) for the coupling magnet. In this case the average coil temperature about the same as the mandrel (98 versus 96 K).

Fig. 2 shows that three focusing magnets in series **F** will have an average *di/dt* = 40 A s^{-1} during a quench. A single coupling magnet **C1** or **C2** will have a *di/dt* = 25 A s^{-1} when it quenches. When the two spectrometer magnets **S** are hooked in series, *di/dt* of magnet circuit **S** is ~50 A s^{-1}. The match coils M1 and M2 will be connected in series with the corresponding coils in the tracker module at the opposite end of MICE. The average *di/dt* values for circuits **M1** and **M2** are about 60 A s^{-1} and 70 A s^{-1}, respectively.

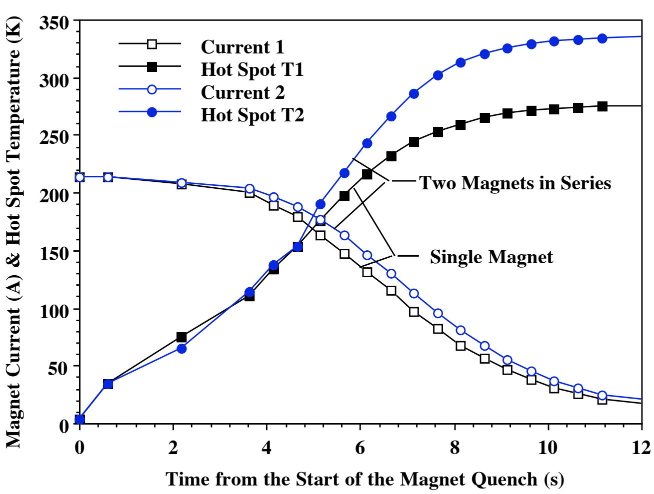

Fig 3. A quench of the one and two coupling magnets.

IV. COUPLING BETWEEN MICE MAGNETS

Table 4 shows an inductance map for the six MICE magnet circuits **S**, **M1**, **M2**, **F**, **C1** and **C2** when MICE is operated in the flip mode. Table 5 shows an inductance map for all of the MICE magnet circuits when MICE is operated in the non-flip mode. The diagonal from the upper left hand corner to the lower right hand corner shows the self-inductance of each magnet circuit. The off-diagonal terms are the mutual inductances between the various MICE magnet circuits. One can see that the mutual inductance is highest between a magnet circuit and its nearest neighbor magnet circuits.

Using the mutual inductance M_{1-2} between two magnet circuits, one can determine the induced voltage V_2 in the second magnet circuit due to a rate of current change di_1/dt in a first magnet circuit. An expression for this is given as follows:

$$V_2 = -M_{1-2}\frac{di_1}{dt} \qquad \text{-1-}$$

The primary power supplies for the MICE magnet circuits generate ±10 V with a maximum current of 300 A [10]. During charging, the *di/dt* in a circuit does not induce enough voltage in other magnet circuits to affect the charging very much. The power supply produces enough voltage to counter the induced voltage from other circuits.

For example a worst-case quench of the focusing magnets can induce 223 V in a coupling magnet circuit when operating in the flip mode and 716 V when operating in the non-flip mode. The *di/dt* in the coupling coil due to these voltages is 0.40 A s^{-1} and 1.27 A s^{-1} respectively for about five seconds. The rate of current change is unlikely to drive the coupling magnet normal through conductor AC loss or by driving the magnet to its critical current. Enough energy may be put into the mandrel to cause the magnet to quench through quench-back. Whether or not a quench in one magnet induces a quench in another magnet through quench-back from the magnet mandrel depends on the available temperature margin in the magnet.

The focusing coil will also affect the first match coil in the tracker module. A worst-case quench of the focusing magnet will induce about 46 V in the match coil in the flip mode and about 79 V in the non-flip mode. The *di/dt* in the first match coil will be 1.74 A s^{-1} and 2.99 A s^{-1}, respectively. As with the coupling coil, neither case is likely to result in a quench due to conductor AC loss or the coil being driven to its critical current. Quench-back in the mandrel can potentially cause quenching in the first match coil, although a quench in a focusing magnet is less likely to induce a quench in the first match coil than it is in the coupling coil because the temperature margin is higher for the entire tracker magnet system.

A quench in one magnet can cause quenching in the whole MICE channel, because the coil circuits are coupled together inductively. A quench in one magnet circuit can induce a quench in an adjacent magnet circuit due to quench-back. A quench in a second circuit is likely to induce a quench in a third circuit and so on, until the whole channel has quenched. The frequency of quenches in MICE will probably determine the acceptable range of average momenta of the muons used in the MICE channel. (The lower the average muon momentum, the lower the currents in the magnets for a given beam in the center of the focusing magnet.)

VI. Concluding Comments

The focusing magnets, coupling magnets and tracker magnets are designed so that they will quench passively without a quench detection system and an active quench protection system. The passive quench protection uses quench-back from the magnet mandrel to the to the magnet coils to spread the quench throughout the magnet coils.

The MICE coils will be connected together in six primary magnet circuits. All three focusing magnets will form one circuit. The coupling coils will be individually powered (two more circuits). Match coil M1 and M2 will each be connected in series with its corresponding coil in the other tracker magnet. The spectrometer solenoid of one tracker magnet will be connected in series with the spectrometer magnet in the other tracker magnet. Tuning of the end coils on each spectrometer magnet will be done using small power supplies. The small tuning supplies have a small effect on the overall magnetic coupling within MICE.

Inductance networks were calculated for the six MICE primary magnet circuits for operation in both the flip and non-flip modes for MICE. As a result of the proximity of the coils and the proposed method of connecting the magnets electrically, every coil in MICE is coupled magnetically with every other coil in MICE. The magnet coupling will affect magnet charging minimally because there is enough voltage capacity in the power supplies to counter the voltage induced by the charging of an adjacent coil circuit.

A quench of one magnet circuit is unlikely to induce a quench in another magnet circuit through AC losses in the conductor or through driving the magnet current beyond its crucial current. A quench in one magnet circuit may cause an adjacent magnet circuit to quench through quench-back from the magnet mandrel. Whether a quench in one MICE magnet circuit causes another magnet circuit to quench depends on the temperature margin of the coils being quenched by the second magnet circuit.

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